The Isotopic Abundances of Magnesium in Stars

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ABSTRACT

Isotopic abundance ratios ^{24}Mg:^{25}Mg:^{26}Mg are derived for 20 stars from high-resolution spectra of the MgH A-X 0-0 band at 5140Å. With the exception of the weak G-band giant HR 1299, the stars are dwarfs that sample the metallicity range -1.8 < [Fe/H] <0.0. The abundance of ^{25}Mg and ^{26}Mg relative to the dominant isotope ^{24}Mg decreases with decreasing [Fe/H] in fair accord with predictions from a recent model of galactic chemical evolution in which the Mg isotopes are synthesised by massive stars. Several stars appear especially enriched in the heavier Mg isotopes suggesting contamination by material from the envelopes of intermediate-mass AGB stars.

Subject headings: magnesium: stars: abundances:

1. Introduction

Observational investigations of the chemical evolution of the Galaxy involve the determination and interpretation of elemental abundances for stellar samples. Many studies draw on the local stellar population which is a mix of disk and halo stars. Results of the abundance analyses are commonly expressed as the variation of the elemental abundance with respect to the iron abundance, i.e., the run of [el/Fe] versus [Fe/H] where, as usual, [X] = $\log_{10}(\mathrm{X})_{star}$ - $\log_{10}(\mathrm{X})_{\odot}$. In this paper, we present measurements of the relative abundances of the stable isotopes of magnesium of which the major isotope is the even-even nucleus ^{24}Mg and the minor isotopes are the neutron-rich ^{25}Mg and ^{26}Mg. Our measurements of stellar isotopic abundances are made from high-resolution spectra of a portion of the MgH $\mathrm{A}^2\Pi$ - $\mathrm{X}^2\Sigma^+$ $\Delta v = 0$ band near 5140Å. Approximately 20 stars with iron abundance from [Fe/H] $\simeq$ 0 to $\simeq -1.8$ were analysed for their Mg isotopic ratios which are compared to the predicted evolution of these ratios.

Synthesis of magnesium occurs primarily in the carbon and neon burning shells of massive stars prior to their deaths as Type II supernovae (Arnett & Thielemann 1985). In the carbon shell whose composition is affected by prior He-burning, ^{25}Mg and ^{26}Mg are abundant because He-burning activated the neutron source $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ and the neutron capture reaction $^{25}\mathrm{Mg}(n,\gamma)^{26}\mathrm{Mg}$ converted some ^{25}Mg to ^{26}Mg. The yield relative to ^{24}Mg of the neutron-rich isotopes - ^{25}Mg and ^{26}Mg - is predicted to increase with the initial metallicity of the massive star, and, more specifically, with the neutron excess. In the case of the unburnt carbon layers, a key factor is the ^{22}Ne abundance which is determined by a star's initial abundance of C, N, and O. Hydrogen burning by the CNO-cycles ensures that the initial combined abundances of the C, N, and O are converted primarily to ^{14}N which during He-burning is converted to ^{22}Ne through to α-captures. Models of Population I and II $25M_{\odot}$ stars evolved through hydrostatic burning and through the supernova explosion confirm the simple expectations (Woosley & Weaver 1982).

Observational evidence of a decline in metal-poor stars of the abundance of ^{25}Mg and ^{26}Mg relative to ^{24}Mg was provided first by Tomkin & Lambert (1980) from an analysis of high-resolution spectra of MgH lines in the subdwarf Gmb 1830 (HD 103095). The observed abundances of ^{25}Mg and ^{26}Mg were in fair agreement with Woosley & Weaver's calculations. Additional studies of stars spanning the range [Fe/H] $\simeq$ -1 to $\simeq$ +0.5 have been reported - see early work by Boesgaard (1968) and Bell & Branch (1970) and more recent work with spectra recorded with solid state detectors by Barbuy (1985, 1987), Barbuy, Spite, & Spite (1987), Lambert & McWilliam (1986), and McWilliam & Lambert (1988).

Recently, Timmes, Woosley, & Weaver (1995) have taken an extensive grid of predicted yields of Mg isotopes (and many other nuclides) from massive stars (Woosley & Weaver 1995), and built a model of chemical evolution of the solar neighborhood that predicts the relative abundance of many elements including the Mg isotopes: the predicted isotopic abundance ratios ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg decrease sharply with decreasing metallicity [Fe/H]. The principal goal of our new investigation was to provide accurate determinations of the isotopic

Mg abundances for a sample of stars with which to test Timmes et al.'s predictions.

2. Observations

The stars listed in Table 1 were observed at McDonald Observatory with the 2.7m Harlan J. Smith reflector and its coudé spectrograph. Two cameras were used for this project. With the 6-foot camera, a single order of an echelle grating was isolated with an interference filter: a 10Å interval around 5135Å was recorded on a Tektronix CCD at a resolving power of approximately 150,000. Observations were also made with the *2dcoudé* camera (Tull et al. 1995) where multiple orders of an echelle are separated by prisms and recorded on a Tektronix 2048 $\times$ 2048 CCD. At the order used for our observations, spectral coverage is not continuous. A majority of the observations were made with the interval 5125 to 5145Å in the central order placed on the CCD. Figure 1 shows a large part of this order for the slightly metal-poor star HD 55458 (G88-14). Principal lines of ^{24}MgH are identified below the spectrum. The resolving power was about 160,000 for most observations but 200,000 for some. When necessary, multiple exposures of about 30 minutes were co-added to achieve the desired high signal-to-noise ratio. All observations were reduced in the standard way using IRAF procedures.

MgH lines are spread across the observed regions but few lines are suitable for analysis of the isotopic abundances owing to blending with identified and unidentified lines. McWilliam & Lambert (1988) recommended three MgH lines in the observed window for use in determining the isotopic abundances. These are shown in Figure 2 which gives expanded plots of the spectrum of G 88-14. The recommended feature at 5134.6Å which is a blend of the $Q_1(23)$ and $R_2(11)$ lines from the 0-0 band; McWilliam and Lambert give accurate wavelengths for all isotopic components for this and their other recommended features. The line is obviously asymmetric with a trailing red wing due to the contributions of the less abundant species ^{25}MgH and ^{26}MgH. This line is flanked by slightly weaker MgH lines that also feature a trailing red wing. Comparison with synthetic spectra shows that, although the red wings of these lines appear to be carbon copies of the 5134.6Å line, other lines contribute such that the isotopic abundances cannot be reliably extracted from them (Tomkin & Lambert 1980; McWilliam & Lambert 1988). The other recommended MgH features are shown too in Figure 2. The line at 5138.7Å, a blend of the ^{24}MgH lines 0-0 $Q_1(22)$ and 1-1 $Q_2(14)$, is in the wing of strong atomic lines. The third feature at 5140.2Å is also an unresolved blend of two ^{24}MgH lines (0-0 $R_1(10)$ and 1-1 $R_2(4)$). At our resolution, the ^{26}MgH pair of lines is effectively resolved from the ^{24}MgH and ^{25}MgH lines. Our spectra are of a resolving power greater by a factor of 2 to 3 than previously used for Mg isotopic analyses.

3. Analysis

Since the method of analysis follows closely that described by McWilliam & Lambert (1988) and earlier by Tomkin & Lambert (1980), a brief description will suffice. Synthetic spectra are generated and fitted to the observed spectrum. Three MgH features (Figure 2) are used to extract the isotopic abundances – see McWilliam & Lambert (their Table 2) for

the description of the features between 5134 and 5140Å and their Table 3 for laboratory measurements of these and other MgH lines. All known MgH lines were included in the synthetic spectra, as well as many atomic lines.

Model atmospheres were computed using the program ATLAS9 (Kurucz 1993). Defining parameters T_{eff}, log g, and [Fe/H] were set as follows: [Fe/H] is provided from the Strömgren indices (b - y), m_1, and c_1 (Schuster & Nissen (1989, eqn. 3); T_{eff} is estimated from Strömgren indices (b - y) and c_1, and [Fe/H] using a relation from Alonso et al. (1996, equation 9); log g is obtained from the Hipparcos parallax using the recipe described by Nissen, Høg, & Schuster (1997). Adopted parameters are summarized in Table 1. We also give there [Fe/H] determined from spectroscopy by Tomkin & Lambert (1999), or as found from a search of references provided by SIMBAD. Adopting the spectroscopic [Fe/H] in the computation of the model atmosphere would have no impact on the determination of the isotopic Mg abundances. The exercise was carried out primarily to ensure that, in a comparison with theoretical predictions (Sec. 4), the isotopic Mg abundances were paired with a reliable estimate of [Fe/H].

In general, the photometric and spectroscopic estimates of [Fe/H] are in good agreement. In discussing the relation between isotopic Mg abundances and [Fe/H], we have given precedence to the spectroscopic [Fe/H] which is often based on several consistent determinations even when a single reference is cited in Table 1. The accuracy of the [Fe/H] estimate is probably ± 0.1 dex or slightly better. There is one case for which photometric and spectroscopic estimates differ greatly: HD 108564 for which [Fe/H] = -0.52 from photometry and -1.18 from spectroscopy. This star is discussed later as possibly 'peculiar' from the point of view of the isotopic Mg abundances. A second star deserves comment: G87-27 was given a metallicity of -1.45 by Carney et al. (1994) but our syntheses of atomic lines gives [Fe/H] = -0.42, a value in good agreement with the photometric determination. We adopt our spectroscopic estimate but reinvestigation would be desirable as our spectral window contains very few unblended weak atomic lines.

The synthetic spectrum program, MOOG, based on the original version by Sneden (1973) was used. A microturbulence of 1 km s^{-1} was assumed for all the stars, and the macroturbulence in the range of 1 – 3.5 km s^{-1} was adjusted to match observed line widths. The instrumental profile was taken from thorium lines in the spectrum of a Th-Ar hollow cathode lamp. The C_2 molecule's Swan system contributes many lines. Following Tomkin & Lambert (1980), the strength of a C_2 line was fixed using a close triplet of lines near 5135.6Å (Figure 2). In the coolest stars, an unidentified line contributes to the stellar feature at this wavelength but the C_2 contribution remains measureable. Lines of the following elements were also included: C, Mg, Sc, Ti, Cr, Fe, Co, Ni and Y lines but in most cases made no significant contribution to the chosen MgH features.

For each star, an initial synthetic spectrum was computed with the isotopic abundances set to ratios of ^{24}Mg:^{25}Mg:^{26}Mg=80:10:10, a mix essentially equal to the terrestrial benchmark ratios of 78.99:10.00:11.01 (de Bièvre & Barnes 1985). We refer to these ratios as the solar ratios. The Mg abundance was adjusted to fit

the ^{24}MgH lines of the three 'isotopic' features and of other clean MgH lines. Then, the ^{25}Mg and ^{26}Mg abundances were adjusted by trial and error until the profiles of the three recommended features were fit satisfactorily. Comparison of the observed and best-fitting synthetic spectra clearly shows that, although other MgH features clearly indicate the presence of ^{25}MgH and ^{26}MgH lines, features other than the recommended trio are stronger than predicted indicating either the presence of unidentified weak blends or quite substantial departures from the predicted rotational line strengths of the MgH lines. Differences between observed and best-fitting synthetic spectra are similar from one star to the next.

A sample comparison of observed and synthetic spectra is shown in Figure 3 for HD 23439A, a metal-poor star ([Fe/H] = -1.1). The adopted best fit is for the ratios ^{24}Mg:^{25}Mg:^{26}Mg = 78:13:9. The presence of ^{25}Mg and ^{26}Mg is umistakeable, as shown by the very poor fit of the synthetic spectrum (dashed line) computed with ^{24}Mg alone (and other non-MgH lines). All MgH lines in the illustrated interval confirm the presence of ^{25}MgH and ^{26}MgH. Equally good fits are obtained to the three recommended MgH features. The dotted lines corresponding to ratios of 72:16:12 and 83:10:6, which are clearly unacceptable fits to the observed spectrum, provide an indication of the measurement uncertainties. Note that MgH lines other than the recommended trio (e.g., lines at 5134.2Å, 5135.1Å, and 5138.3Å) have stronger red wings than predicted by the best-fitting synthetic spectrum.

A second comparison (Figure 4) involves the N-rich dwarf HD 25329 whose MgH lines are stronger than those of HD 23439A; HD 25329 is more metal-poor by about 0.7 dex but of a lower temperature. Again, the three recommended MgH features give consistent isotopic ratios. The best fit is obtained with the ratios ^{24}Mg:^{25}Mg:^{26}Mg = 85:8:8. The dotted lines show synthetic spectra corresponding to the ratios 89:6:5 and 81:10:9 that are considered not to fit the observed spectrum.

The third selected comparison (Figure 5) is for 12 Oph, a star of solar metallicity. In this case, the recommended features at 5138.7Å and 5140.2Å give very similar results; note how essential it is to fit the wings of the atomic lines near 5139.3Å. The third recommended feature at 5134.6Å is obviously contaminated with a blend in its red (and also in the blue) wing. Based on the two apparently unblended features, the best fit is for ^{24}Mg:^{25}Mg:^{26}Mg = 74:12:13 with the dotted lines providing unsatisfactory fits with the ratios 69:15:16 and 80:9:10.

In the above examples, syntheses represented by the dotted lines correspond to isotopic mixtures that clearly do not fit the recommended MgH features. If the isotopic ratios were the sole adjustable variable, the error in the ratios would be less than the few per cent error represented by the dotted lines. An allowance for the observed spectrum's S/N ratio and a consideration of the precision with which the continuum may be set would not increase the errors beyond those represented by the dotted lines. Although the predicted strength of a MgH line is sensitive to the adopted atmospheric parameters, the isotopic ratios are quite insensitive. In those cases where the ^{24}MgH lines are strong, the abundance ratio of ^{25}Mg and ^{26}Mg with respect to ^{24}Mg is most sensitive to the adopted microturbulence.

Alternative choices for the microturbulence lead to a change in the ^{24}Mg abundance needed to fit the cores of the MgH features but to very little to no change in the red wing to which the ^{25}MgH and ^{26}MgH lines contribute. In the case of HD 23439A, for example, a reduction of the microturbulence from 1.0 km s^{-1} to 0.5 km s^{-1} requires an increase in the ^{24}Mg abundance by about 0.02 dex which corresponds to a less than 1% reduction in the isotopic abundance ratios ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg. An increase of the microturbulence from 1.0 to 1.5 km s^{-1} results in a smaller percentage increase of the ratios. The effects are slightly larger for the stars with the strongest MgH features. In summary, if the isotopic abundances ^{24}Mg:^{25}Mg:^{26}Mg are expressed as x:y:z where x + y + z = 100, the errors in y and z are about ± 2 or slightly better for metal-poor stars and possibly worse for cool solar-metallicity stars like 12 Oph. Greater blending of the ^{25}MgH feature with the ^{24}MgH line leads to a somewhat greater uncertainty for the ratio y/x. If an isolated MgH were available in the spectra, comparison of the red isotope-contaminated wing with the blue wing would provide the combined ratio (^{25}Mg + ^{26}Mg)/^{24}Mg with greater certainty than either of the individual ratios ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg. Unfortunately, as our illustrations of short segments of the spectra suggest, such unblended lines do not exist. Our tests indicate that the ^{26}Mg/^{24}Mg ratio is more accurately determined from our spectra than the ^{25}Mg/^{24}Mg ratio.

Isotopic magnesium abundances have been reported previously for six of the program stars. In general, our results from higher quality spectra are consistent with published values. Tomkin & Lambert (1980) analysed Gmb 1830 and μ Cas but used only one of the three features subsequently recommended by McWilliam & Lambert (1988), and in the former case included three secondary MgH lines. Our and the earlier results for Gmb 1830 are identical: ^{24}Mg:^{25}Mg:^{26}Mg = 93:4:3. For μ Cas, we find a slightly lower concentration of the heavier isotopes: 85:7:8 now vs 80:10:10 (≅ solar) then. Our use of two additional recommended MgH lines and higher quality spectra may account for the small difference between these results.

Barbuy et al. (1987) analysed HD 23439B[1] and HD 25329. Our results for HD 23439A of 84:8:8 are in very good agreement with the ratios 86:7:7 by Barbuy et al. The result is similar for HD 25329: 85:8:8 from Table 1 and 90:5:5 from Barbuy et al. Comparison of the observed spectrum with that of Gmb 1830 clearly shows the greater presence of ^{25}Mg and ^{26}Mg in HD 25329. Similarly, Figure 6 shows that HD 23439A has markedly greater concentration of ^{25}Mg and ^{26}Mg than Gmb 1830. Barbuy et al. (1987) show the spectrum of HD 25329 around 5135Å. The higher resolving power of our spectrum is clearly seen by comparing the central depths of the lines which are deeper in our spectrum (e.g., the MgH line at 5134.6Å has a central depth of 0.46 against 0.58 in Barbuy et al.'s spectrum), and in the clearer presence of the inflections and partially resolved lines due to ^{25}MgH and ^{26}MgH in our spectrum. In addition, the ^{26}MgH line in our spectrum is well resolved in the 5140.2Å feature.

Tau Ceti and HR 1299 were analysed by McWilliam & Lambert (1988). For τ Ceti, our

[1] Barbuy et al. refer to the star observed as HD 23439B but list the V magnitude of HD 23439A. Star B is 0.6 magnitudes fainter than A.

ratios are 75:15:9 and the former estimates were 83:7:10. Barbuy (1985) obtained 84:7:7. For HR 1299, our result 72:18:10 compares with the previous result 80:10:10. In both cases, the disagreement concerns the ^{25}Mg/^{24}Mg ratio. Inspection of a set of syntheses for these and other stars with more ^{25}Mg than ^{26}Mg indicates that an isotopic mixture with nearly equal parts ^{25}Mg and ^{26}Mg does not provide a satisfactory fit to the observed spectra. We suppose that the higher resolution of our spectra enables us to derive the ^{25}Mg abundance where others may have assumed that ^{25}Mg and ^{26}Mg were of similar abundance.

4. Results and Discussion

4.1. Chemical Evolution of ^{25}Mg and ^{26}Mg

Our isotopic ratios may be compared with predictions based on the assumption that the magnesium isotopes are exclusively a product of hydrostatic burning in massive stars and are ejected by the supernova explosion. We comment later on a possible contribution from intermediate-mass AGB stars that synthesise ^{25}Mg and ^{26}Mg in the course of operating the s-process by the neutron source ^{22}Ne$(\alpha,n)^{25}$Mg. Extensive calculations of nucleosynthesis by massive stars (Woosley & Weaver 1995) may be used to illustrate the predicted metallicity dependence of the isotopic Mg ratio. We take as a representative model of a $30M_{\odot}$ star from their series B. Woosley & Weaver characterize the composition of the ejecta in two ways, as mass in $M_{\odot}$, and as a production factor which is the mass fraction of a nuclide contained in the ejecta relative to mass fraction in the adopted standard solar mix. If the production factors predicted for a collection of different nuclides are numerically equal, these nuclides are produced in standard proportions. For our present purpose, we compare the ratio (here, p_{25}) of the production factors of ^{25}Mg and ^{24}Mg for the 30B models of different initial composition. The ratios for ^{26}Mg and ^{24}Mg behave very similarly. Obviously, in the case that $p_{25} = 1$, this isotopic ratio in the ejecta is the standard value. The predicted values are 0.78, 0.086, 0.025, 0.024, and 0.056 for models having the initial mass fraction $Z/Z_{\odot} = 1$, 0.1, 0.01, 10^{-4}, and 0.0. The value of p_{25} at a given Z is weakly dependent on a model's mass. The initial decline of p_{25} from $Z = Z_{\odot}$ to $Z = 0.1Z_{\odot}$ is presumably the result of ^{25}Mg production via ^{22}Ne$(\alpha,n)^{25}$Mg and the decline in the abundance of the seed ^{22}Ne. A shallowing of the decline for $Z < 0.01Z_{\odot}$ likely reflects a primary production of the n-rich isotopes. Since p_{25} is weakly dependent on stellar mass, the predicted isotopic ratios are rather insensitive to the assumed form of the initial mass function, and evolution of the ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg in the Galaxy may be qualitatively predicted from this discussion.

One expects a ratio of ^{i}Mg/^{24}Mg of a few per cent from very low metallicities until $Z \simeq 0.01Z_{\odot}$ and then an increase that steepens as $Z = Z_{\odot}$ is reached. Timmes et al.'s (1995) comprehensive theoretical study of the chemical evolution of the solar neighborhood includes quantitative predictions of the isotopic ratios ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg. Predicted trends of ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg vs [Fe/H] are almost identical with ^{26}Mg/^{24}Mg about 6% greater at a given [Fe/H]. Timmes et al. considered the ejecta of Type II and Type Ia supernovae. Both types of supernovae return iron to the

interstellar medium but only the Type II supernovae return magnesium in appreciable quantities. These predictions (Figures 7 and 8) for the isotopic Mg abundances appear to be the only extant predictions that incorporate predicted compositions of supernovae ejecta in a model of the solar neighborhood.

Contributions from intermediate mass stars were not considered by Timmes et al. These stars may synthesise ^{25}Mg and ^{26}Mg when, as AGB stars, they experience the s-process. These products get into the interstellar medium when an AGB star sheds its envelope. Constraints on contributions from AGB stars should be obtained from observations of other abundances that they may contribute, principally N and the s-process elements. It may then be important to the story of the Mg isotopic abundances that Timmes et al.'s standard predictions failed to fit the observation that [N/Fe] $\simeq 0$ over the range -2.5 $<$ [Fe/H] $<$ 0 for which N abundances are presently known. These predictions show [N/Fe] declining steeply for [Fe/H] $\leq$ -1.5. Possibly, the nitrogen deficiency of the galactic chemical evolution model may be made up from intermediate-mass stars which may manufacture large amounts of N by CN-cycle H-burning of C dredged-up from the He-shell, particularly in a terminal evolutionary phase when the star develops a 'hot-bottomed-convective-envelope'.

Pagel & Tautvaišienė (1997) propose a model to account for the observed abundances of r and s-process species that includes an s-process contribution from AGB stars. Norris (1999) suggests that these stars may also account for the early evolution of the N abundances. Massive stars are presumed responsible for the r-process. Pagel & Tautvaišienė suppose the s-process contributions to be delayed with respect to the r-process. Delays of about 37 Myr and 2.7 Gyr were found from a fit to the observed abundances, that is progenitor masses of about $8M_\odot$ and $1.5M_\odot$ respectively. The effects on galactic abundances of the ejecta from the $1.5M_\odot$ stars occurs only for [Fe/H] $\geq$ -0.7. These low-mass stars most probably are ineffective contributors of the Mg isotopes and certainly not competititve with massive stars. From their first contributions at [Fe/H] $\sim$ -2.4 to [Fe/H] = -0.7, the $8M_\odot$ stars control s-process abundances.

Copious amounts of ^{25}Mg and ^{26}Mg are expected from the $8M_\odot$ stars that should run the s-process with the $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$ neutron source. Yields of s-process species should scale approximately with a star's initial metallicity, i.e., the s-process is, in the language of the subject, a secondary not a primary process. However, Pagel & Tautvaišienė's fit to the observed abundances requires primary production of s-process species by the $8M_\odot$ (and $1.5M_\odot$) stars. This, as they noted, would suggest that an alternative neutron source, probably the $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ reaction, operated with very little contribution from the ^{22}Ne source. The ^{13}C source is expected to be dominant in any case in the $1.5M_\odot$ stars. Although detailed calculations should be made, it is likely that operation of the ^{13}C source does not lead to major enrichments in the stellar envelope (and subsequently in the ejecta) of ^{25}Mg and ^{26}Mg relative to ^{24}Mg. If true, the expectation is that the massive stars control galactic chemical evolution of the Mg isotopes despite their probable failure to account for the observed N abundances.

Thanks to the larger isotopic wavelength shift, the ^{26}MgH lines are less blended with

the strong ^{24}MgH parent lines than the ^{25}MgH lines. Then, the ^{26}Mg abundance is likely more reliably determined than the ^{25}Mg abundance. We begin by comparing the observed and predicted ^{26}Mg/^{24}Mg ratios. Our sample contained a minority with known abundance anomalies (e.g., the N-rich subdwarf HD 25329) but the majority were known to have normal abundances for their metallicity. It was anticipated that some of the minority might also have anomalous isotopic ratios and so it proved. What was not anticipated was that stars considered or assumed to be of normal composition for their metallicity would possess anomalous isotopic ratios.

In the comparison made in Figure 7 between predicted and measured ^{26}Mg/^{24}Mg ratios, we distinguish normal and peculiar stars where the latter group comprises stars with anomalous elemental abundances for light and/or heavy elements but not all such peculiar stars have odd isotopic ratios. Figure 7 shows that the measured isotopic ratio for the normal stars and the predictions are in general agreement: the ratio ^{26}Mg/^{24}Mg declines with decreasing [Fe/H] in line with the predicted trend. It is apparent too that there is a scatter across the sample of normal and peculiar stars showing that the isotopic ratio at a given [Fe/H] exceeds the measurement errors of the isotopic ratio and [Fe/H]. That the scatter is in part intrinsic is well shown by Figure 6 where spectra of Gmb 1830 and HD 23439A are plotted. It is seen that the strengths of the ^{24}MgH-dominated cores of the two identified recommended MgH features (also, the MgH feature at 5138.35Å) are very similar but the red wings to which ^{25}MgH and ^{26}MgH contribute are pronounced for HD 23439A but not for Gmb 1830. Since the atomic line at 5137.4Å is symmetrical in both spectra, the stronger asymmetry must be due to the heavier Mg isotopes and to a greater isotopic ratio for these isotopes in HD 23439A. Peculiar stars like HD 23439A are discussed following remarks on the general trend of ^{26}Mg/^{24}Mg and ^{25}Mg/^{24}Mg with [Fe/H]. The sample of normal stars may be too small and the errors of measurement of such a size that the evidence for intrinsic scatter is not quite so striking.

There is a hint that the observed ratio ^{26}Mg/^{24}Mg is consistently greater than predicted. Timmes et al. note that their prediction of the iron yield from Type II supernovae depends on the mass cut between the collapsed object (neutron star or black hole) and the ejecta. Since yields of lighter elements, including magnesium, are unaffected by the positioning of the mass cut, the effect of a change in the mass cut is to translate the predicted ^{26}Mg/^{24}Mg vs [Fe/H] along the [Fe/H] axis; for example, a slightly shallower mass cut independent of a star's initial composition reduces the [Fe/H] that corresponds to a given isotopic ratio. A change of the mass cut with [Fe/H] would, of course, change the shape of the predicted curve. There is a second way to affect the predicted relation. Iron is contributed by both Type II and Type Ia supernovae. The Type Ia supernovae provide iron but very little magnesium and, hence, if their contribution relative to that of the SN II is altered, the predicted curve in Figure 7 is translated along the [Fe/H] axis. In addition, the contribution from Type Ia supernovae is delayed relative to the almost instantaneous contribution from the Type II supernovae. Therefore, a change in the adopted lifetime of the Type Ia precursors changes the shape of the predicted curve around the metallicity at which the Type Ia supernovae begin to contribute to [Fe/H], and displaces the

curve over the [Fe/H] range for which the Type Ia and II supernovae are contributing in tandem; for example, if the lifetime for the precursors is longer than assumed by Timmes et al., the predicted curve is translated to lower [Fe/H]. But, as noted above, Timmes et al.'s choices for the various quantities that affect the translation and shape of the predicted ^{26}Mg/^{24}Mg relation result in a relation that fits our observations of ^{26}Mg/^{25}Mg ratios remarkably well. If the Mg isotopes are contributed partly by AGB stars, an intrinsic scatter in the isotopic ratio at a given [Fe/H] would not be surprising in light of the evidence that there is an intrinsic scatter in the ratios [s/Fe] at a given [Fe/H] (Edvardsson et al. 1993).

Measurements of the ^{25}Mg/^{24}Mg are somewhat less precise because the ^{25}MgH line is more severely blended with the ^{24}MgH line than is the ^{26}MgH line. Figure 8 shows that ^{25}Mg/^{24}Mg mimics the decline of the ^{26}Mg/^{24}Mg ratio with decreasing [Fe/H]. Two differences are noticeable: the scatter of the measured ^{25}Mg/^{24}Mg ratios about a mean relation is larger than for the ^{26}Mg/^{24}Mg ratios, and the mean relation is decidedly offset from the predicted curve. There is a clear tendency for the measured ^{25}Mg/^{24}Mg ratios to be displaced by either about 0.3 dex in [Fe/H] or 0.03 in ^{25}Mg/^{24}Mg. As detailed above, simple adjustments to the predictions may be envisaged to bring observation and theory into agreement: alter the mass cut in Type II supernovae or change the ratio of Type II to Type Ia supernovae that contributed to the chemical evolution of the disk. The displacement may be slightly larger than for ^{26}Mg/^{24}Mg. If true, this would require additionally a change in the relative yields of ^{25}Mg and ^{26}Mg from Type II supernovae. It would be of interest in this connection to have an assessment of the sensitivity of the yields to the uncertainties in the key nuclear reaction rates influencing synthesis of the Mg isotopes. A comparison of yields from massive stars (Hoffman et al. 1999) suggests that these uncertainties are certainly not an insignificant contributor to predicted evolution of the Mg isotopes.

Timmes et al. checked their predictions against measurements drawn from the literature of the ^{25}Mg/^{24}Mg ratio in dwarfs and subgiants. Timmes et al. aver that "for [Fe/H] $\geq$ -1.0, the calculations agree fairly well with the magnesium isotope ratios found in disk dwarfs". Inspection of the comparison (their Figure 16) suggests, however, that the scatter of the collated observations is so large that "fairly well" must be an elastic qualifier. Our present results would likely cause Timmes et al. to reiterate their remark but with the qualifier 'fairly' expunged!

For low metallicities, [Fe/H] ≤ -1.0, Timmes et al. selected three additional data points: Tomkin & Lambert's (1980) original result for Gmb 1830 which fell near the predicted curve and two results from Barbuy (1985) that do not at all fit the predicted curve: HD 24616 at [Fe/H] = -1.5 had slightly sub-solar abundances of ^{25}Mg and ^{26}Mg and HD 188510 at [Fe/H] = -1.8 had solar isotopic ratios. Inspection of the literature shows that the iron abundance of HD 24616 is higher than adopted by Barbuy. When [Fe/H] = -0.8 (François 1988; Pilachowski, Sneden & Booth 1993) is adopted, Barbuy's isotopic ratios fit the predicted curves. HD 188510 is not so simply brought into conformity; the adopted metallicity is confirmed by recent spectroscopic analyses, e.g., Beers et al. (1999) select [Fe/H] = -1.53

from a literature survey. Our observations of this star at a resolving power of 200,000 show very weak MgH features: the 5138.7Å feature is just 5% deep in good agreement with a prediction based on Barbuy's adopted atmospheric parameters. If isotopic ratios are solar, the ^{25}MgH and ^{26}MgH lines would be at most about 0.5% deep. Our exploratory spectrum had a S/N ratio of about 60 so that no information except high upper limits can be given for the ratios. Barbuy's spectrum was at a resolving power of 80,000 - 100,000 and the quality is given as 'bad' which would seem to imply a S/N of 100 or less at which the quoted isotopic ratios are not determinable unless the MgH were very much stronger than at the time of our observation.

Timmes et al. overlooked a few measurements: Lambert & McWilliam (1986) set an upper limit of 3% to the ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg ratios for the subgiant ν Indi with [Fe/H] = -1.5; Barbuy et al. (1987) reported isotopic ratios of 6 to 8% for three additional stars with [Fe/H] in the range -1.1 to -1.6. The upper limits are consistent with the predictions and our measurements. Barbuy et al.'s measured ratios exceed the predictions.

Observers' views of the evolution of the Mg isotopic ratios have evolved. Tomkin & Lambert (1980) discovered the low abundance of the neutron-rich isotopes in Gmb 1830, a result confirmed here, and noted that it was consistent with synthesis of the Mg isotopes by massive stars. In contrast, Barbuy's (1985) pioneering survey of the Mg isotopes in 24 stars led her to note that "values [of the isotopic ratios] close to the solar ratios ^{24}Mg:^{25}Mg:^{26}Mg = 79:10:11 are generally found" for the range -1.5 < [Fe/H] <0. Barbuy et al. (1987), who analysed three halo dwarfs and two super-metal-rich dwarfs, combined their results with those in the literature to suggest a trend for the isotopic ratios: ^{i}Mg/^{24}Mg where i = 25 or 26 has the solar ratio for [Fe/H] > -0.5, and is lower by 0.4 dex for halo stars with [Fe/H] < -1.0 with a smooth transition between the solar and halo ratios between [Fe/H] of -1.0 and -0.5. Such a relation provides an adequate fit to our results for the ^{25}Mg/^{24}Mg ratio but our results for the ^{26}Mg/^{24}Mg ratio, which are more accurate than those for ^{25}Mg/^{24}Mg clearly indicate a continuous decline in the ratio with decreasing [Fe/H] on the plausible assumption that Gmb 1830 and ν Ind rather than HD 25329 and its peculiar cohorts are taken to define the decline. In light of other abundance peculiarities displayed by HD 25329 and several other peculiar stars, the galactic evolution of the Mg isotopes is most probably better defined by normal stars like Gmb 1830.

4.2. Peculiar Stars

Our intent was that the label 'peculiar' should be attached only to stars in our sample known to have anomalous abundances of one or more elements. By this definition, the peculiar stars are HR 1299, HD 23439A and B, HD 25329, and HD 134439 and HD 134440. An additional star – HD 108564 – is termed peculiar on the basis of above average relative abundances of ^{25}Mg and ^{26}Mg.

HD 108564 is notable for the fact that the spectroscopic estimate of [Fe/H] is appreciably lower than the photometric estimate. Our syntheses give [Fe/H] = -0.9 from a few strong lines. Ryan & Norris (1991) estimate

[Fe/H] = -1.12 from the U - B ultraviolet excess, an estimate oddly inconsistent with the Strömgren photometry but consistent with the spectroscopic estimate. The star is listed as a CH subdwarf by Bartkevičius (1996) but it is then surprising that Tomkin & Lambert (1999) who specifically investigated heavy elements did not report their overabundance. Twarog & Anthony-Twarog (1995) report photometric measurements of the Ca II H and K lines. These show the star to be quite unusual in that the *hk*-index is stronger than is measured for [Fe/H] $\sim$ 0 stars; metal-poor stars show the expected weaker *hk*-index. This anomalous *hk*-index may be indicative of unusual molecular line blanketing. Further spectroscopic examination is warranted. We shall assume that [Fe/H] = -1.18 is the star's metallicity. HD 108564 is greatly overabundant in ^{25}Mg and ^{26}Mg for this metallicity. The isotopic ratios are normal for the photometric metallicity.

Binary members HD 23439A and B were shown by Tomkin & Lambert (1999) to be enriched in heavy elements relative to other stars of the same metallicity. Enrichments of the measured elements were 0.3 to 0.5 dex for Y, Zr, Ba, and Nd. The pair are mild CH (dwarf) stars whose abundance anomalies are likely to be primordial rather than, as now generally assumed for CH and Ba stars, a product of mass transfer across a binary system; the binary is a wide binary and, in addition, HD 23439B is itself a spectroscopic binary. Both stars are enriched in ^{26}Mg relative to the mean trend, and HD 23439A but not B is enriched in ^{25}Mg relative to other stars of the same metallicity. The ^{26}Mg/^{24}Mg ratios of A and B differ by only 2.5%, which is approximately the error of measurement. The difference for ^{25}Mg/^{24}Mg is about three times larger: 8% (17% for A vs 9.5% for B). To highlight this difference in isotopic ratios, we provide in Figures 9 observed and synthetic spectra covering two of the three recommended MgH lines. For each star we provide the synthetic spectrum (continuous line) computed for that star's derived isotopic ratios and the spectrum (dashed line) computed for its companion's derived ratios. In the case of HD 23439A, the ratios for HD 23439B lead to a slightly weaker red wing of the MgH lines. Unless the restriction that broadening mechanisms be symmetric is relaxed, it is probable that A's isotopic mix is not equal to that of B. In the case of HD 23439B, the MgH lines are stronger and the differences between the synthetic spectra for the A and B ratios are larger. Nonetheless, it is a concern that the principal difference in the isotopic ratios concerns the ^{25}Mg/^{24}Mg ratio derived from the ^{25}MgH lines that are more blended with the ^{24}MgH line than the ^{26}MgH line. Since it would be remarkable if the stars did have different isotopic ratios, we intend to obtain spectra of even higher quality and pay especial attention to the broadening of MgH and atomic lines including a determination of the microturbulence.

These anomalous enrichments of the heavier Mg isotopes may be associated with their *s*-process enrichment, and both may be identified with an abnormal contamination of the stars' natal cloud with ejecta from intermediate-mass AGB stars. Thermal pulses (He-shell flashes) in stars of initial mass of between about 4 and 10$M_{\odot}$ are predicted to release neutrons primarily from the reaction $^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$. These neutrons run an *s*-process with some captured by ^{25}Mg to form ^{26}Mg. Dredge-up from the He-shell into the H-rich convective envelope is predicted

to enrich the envelope markedly in ^{25}Mg and ^{26}Mg as well as the *s*-process products (see review by Lambert 1991). If ejecta from intermediate-mass AGB stars were not severely diluted with interstellar material before new stars were formed, those stars would be enriched relative to typical stars of the same metallicity in both *s*-process elements and the heavier Mg isotopes, as is observed. This discovery would appear to conclude a long search among barium stars for evidence of *s*-processing and isotopic Mg enrichments arising from operation of the ^{22}Ne neutron source in intermediate-mass stars (see, for example, Tomkin & Lambert 1979; McWilliam & Lambert 1988; Malaney & Lambert 1988; Barbuy et al. 1992). A thorough abundance analysis of HD 23439A and B would now be of great interest.

HD 25329 is a remarkably nitrogen-rich star belonging to the class of relatively rare N-rich subdwarfs discovered by Bessell & Norris (1982). A detailed abundance analysis of HD 25329 was reported by Beveridge & Sneden (1994). With respect to normal stars of the same metallicity, HD 25329's principal abundance anomalies are a N enchancement by 0.5 dex (Carbon et al. 1987), and an overabundance of *s*-process elements similar to those shown by HD 23439A and B. Sodium and possibly aluminum may also be slightly overabundant. Beveridge & Sneden thought it likely that the abundance anomalies resulted from contamination of the natal cloud with material ejected by AGB stars, as discussed above for HD 23439A and B. Isotopic Mg ratios of 85:8:8 are similar to those of HD 23439A and B but the ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg ratios are a factor of three greater than those measured for Gmb 1830, a normal star of slightly greater metallicity. This suggests that HD 25329 was enriched in the two heavier Mg isotopes as the other abundance anomalies were formed. Intermediate-mass AGB stars are expected to eject N-rich material with an enrichment of these Mg isotopes. Thus, the Mg isotopic data support and extend Beveridge & Sneden's proposal.

HR 1299 is an example of a weak G-band giant, a rare class of giants with an atmosphere highly contaminated with products of the H-burning CN-cycle, i.e., deficient in ^{12}C but with a low ^{12}C/^{13}C ratio and rich in nitrogen (Cottrell & Norris 1978; Sneden et al. 1978; Day 1980; Lambert & Sawyer 1984). Some stars including HR 1299 are Li-rich relative to similar and normal red giants (Lambert & Sawyer 1984). Since carbon is underabundant by a large factor, blending of MgH lines with C_2 lines is effectively eliminated for HR 1299 and the accuracy of the isotopic Mg ratios enhanced. Our results show that the ratios are essentially normal; whatever processes create a weak G-band giant the isotopic Mg ratios are unaffected (at least for HR 1299) in contrast to the situation found for the N-rich dwarf HD 25329.

Local disk and halo stars show, as a function of [Fe/H], well defined smooth trends in relative abundance: for example, magnesium and other so-called α-elements (Si, Ca, and Ti) are overabundant in stars with [Fe/H] $\lesssim -1$ such that [Mg/Fe] $\simeq 0.4$. Even peculiar stars, HD 25329 for example, may show this overabundance. The common proper motion pair HD 134439 and HD 134440 are exceptional because they are α-poor; King (1997) shows that [Mg/Fe], [Si/Fe], and [Ca/Fe] are each about 0.3 dex less than the values found for the vast majority of halo stars. King speculated that HD 134439 and HD 134440 were accreted by our

Galaxy from a dwarf spheroidal galaxy whose chemical evolution to [Fe/H] = -1.5 was more greatly influenced by Type Ia supernovae than was the halo of our Galaxy. A change in the Type II to Ia supernova rates alters the [Mg/Fe] at a given [Fe/H]. As long as the magnesium comes primarily from Type II supernovae, the Mg isotopic abundance are not expected to be different in α-poor stars and normal stars of the same [Fe/H] provided that massive stars, the progenitors of Type II supernovae, were formed roughly steadily over the life of the dwarf spheroidal galaxy; if massive stars were formed largely in an initial starburst, and Type Ia supernovae subsequently built up the galaxy's iron abundance, the Mg isotopic ratios would be those expected of massive stars more metal-poor than the gas from which HD 1334439 and HD 134440 formed. Our analysis shows that, although the elemental abundance of Mg is peculiar, the isotopic Mg ratios are quite unexceptional being identical to those found for Gmb 1830, a subdwarf of similar [Fe/H] with normal abundances of the α-elements. This result is consistent with the accretion hypothesis. It might be noted that 'accretion' is not demanded either by our observations or by the reported abundance anomalies. If our halo were not everywhere thoroughly mixed, one would expect pockets of star formation occurring in regions more heavily contaminated than the average region with ejecta from a Type Ia supernova. Stars from such regions would be α-poor.

5. Concluding Remarks

These measurements of the isotopic Mg abundances provide confirmation of the predicted reduction of the ^{25}Mg/^{24}Mg and ^{26}Mg/^{24}Mg ratios with decreasing [Fe/H], and show that the Mg isotopes are primarily a product of nucleosynthesis in massive stars. Unfortunately, measurements on normal dwarfs do not extend to metallicities less than [Fe/H] $\simeq -1.5$. At present, the sample of stars known with [Fe/H] < -1.5 have effective temperatures ($T_{\rm eff}$ > 4700K) too high for their spectra to contain MgH lines of an adequate strength for successful isotopic measurements at the expected isotopic ratios of ^{i}Mg/^{24}Mg of about 5% or less. A dedicated search for cooler metal-poor stars is needed to provide suitable targets with which to extend our measurements. It is in the regime [Fe/H] < -1.5 that intermediate-mass AGB stars may contribute to the galactic chemical evolution of nitrogen and the *s*-process elements and possibly also to the evolution of the ^{25}Mg and ^{26}Mg isotopes.

A second and important result of our survey has been the demonstration that some stars known to have an anomalous or peculiar composition are also marked by distinctive isotopic Mg abundances. The N-rich subdwarf HD 25329 and the CH stars HD23439A and B are enriched in ^{25}Mg and ^{26}Mg relative to normal stars of the same metallicity. This enrichment is attributed to local enrichment of their natal clouds with ejecta from intermediate-mass AGB stars. One other star - HD 108564 – is rather similarly enriched but not so obviously distinguished by other abundance anomalies. Not all stars with anomalous compositions have peculiar isotopic Mg ratios: the weak G-band giant HR 1299 and the low-α common proper motion pair HD 134439 and HD 134440 have normal isotopic abundances. This result highlights the fact that the more detailed the information on the chemical composition the greater are the constraints that may be placed

on explanations for the abundance anomalies.

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Fig. 1.— The spectrum of HD 55458 (G88-14) from 5132Å to 5141Å. Locations of the MgH lines are identified below the spectrum. Many of these lines are present in the stellar spectrum but weak blends render them unsatisfactory for the determination of the isotopic abundances. Three lines used to determine the isotopic ratios are marked by an asterisk.

Fig. 2.— The spectrum of HD 55458 (G88-14) from 5134Å to 5136Å showing one of three principal lines used in the isotopic abundance analysis - the line at 5134.6Å(the top panel). The weak feature near 5135.7Å is partly due to lines of the C_2. The lower panel shows the spectrum from 5138Å to 5140.7Å including the recommended features at 5138.7Å and 5140.2Å.

Fig. 3.— The spectrum of HD 23439A from 5134.0Å to 5136Å and from 5138Å to 5140.5Å. The observed spectrum is represented by filled circles. Synthetic spectra are shown for the isotopic ratios ^{24}Mg:^{25}Mg:^{26}Mg = 100:0:0 (dashed line), 78:13:9 (solid line, best fit to the recommended features), and 72:16:12 and 83:10:6 (dotted lines).

Fig. 4.— The spectrum of HD 25329 from 5134.0Å to 5136Å and from 5138Å to 5140.5Å. The observed spectrum is represented by filled circles. Synthetic spectra are shown for the isotopic ratios ^{24}Mg:^{25}Mg:^{26}Mg = 100:0:0 (dashed line), 84:8:8 (solid line, best fit to the recommended features), and 89:6:5 and 81:10:9 (dotted lines).

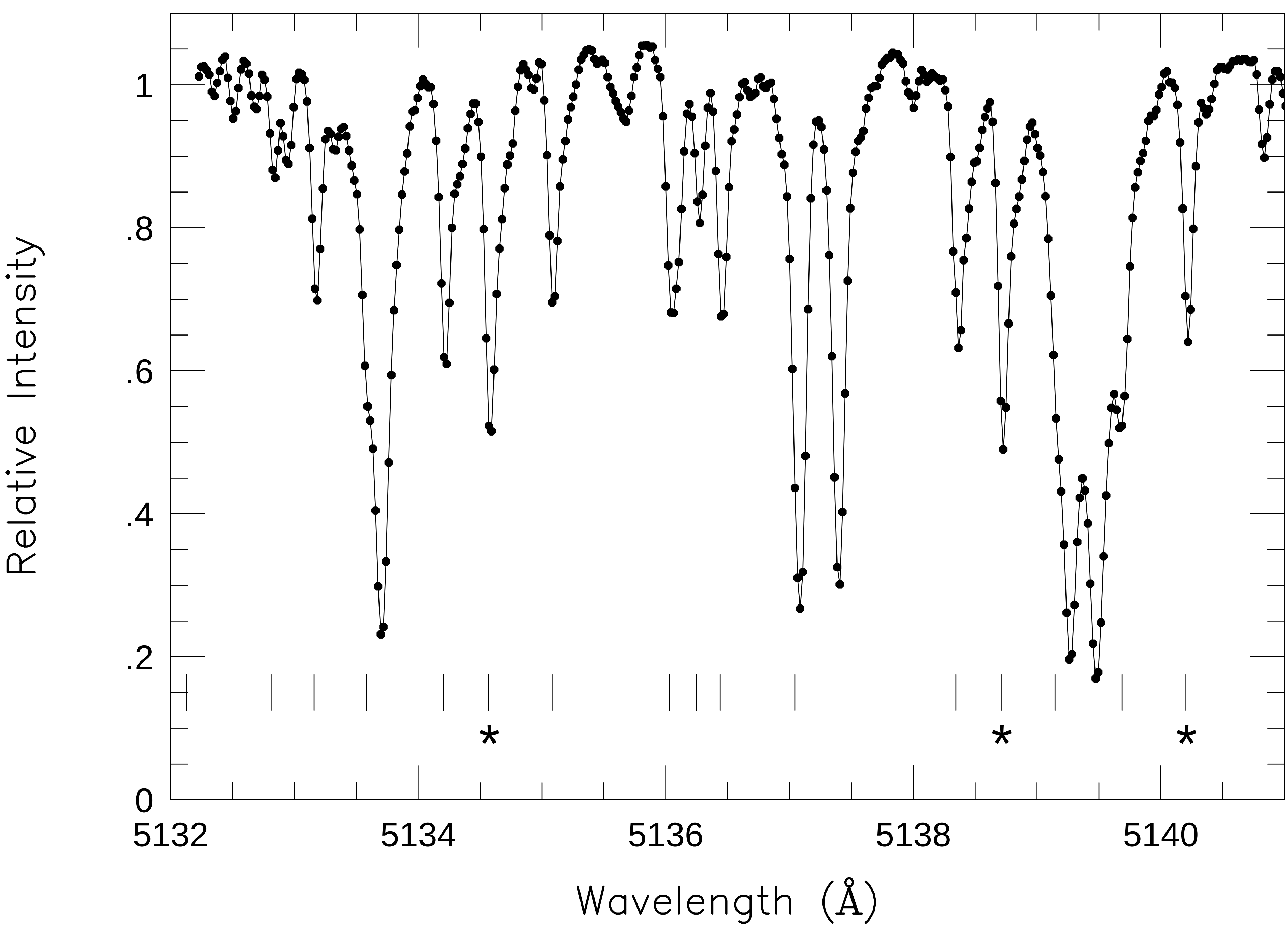
Fig. 5.— The spectrum of 12 Oph from 5134.0Å to 5136Å and from 5138Å to 5140.5Å. The observed spectrum is represented by filled circles. Synthetic spectra are shown for the isotopic ratios ^{24}Mg:^{25}Mg:^{26}Mg = 100:0:0 (dashed line), 74:12:13 (solid line, best fit to the recommended features), and 69:15:16 and 80:9:10 (dotted lines).

Fig. 6.— Observed spectra of Gmb 1830 and HD 23439A showing two of the recommended MgH features. While the depths of the cores of these features are almost the same for the two stars, the red asymmetry to the MgH lines caused by the ^{25}MgH and ^{26}MgH components is striking for HD 23439A but not for Gmb 1830. The dashed lines show the best-fitting synthetic spectra with the isotopic ratios taken from Table 1

Fig. 7.— Isotopic ratio ^{26}Mg/^{24}Mg versus [Fe/H]. Predicted evolution of the ratio from Timmes et al. (1995) is shown by the solid line with the extension to low [Fe/H] represented by the dashed line based on the discussion in the text in Sec. 4.1. Our results are represented by filled and open circles where the latter denote 'peculiar' stars discussed in Sec. 4.2.

Fig. 8.— Isotopic ratio ^{25}Mg/^{24}Mg versus [Fe/H]. Predicted evolution of the ratio from Timmes et al. (1995) is shown by the solid line with the extension to low [Fe/H] represented by the dashed line based on the discussion in the text in Sec. 4.1. Our results are represented by filled and open circles where the latter denote the 'peculiar' stars discussed in Sec. 4.2.

Fig. 9.— Observed and synthetic spectra of HD 23439A and HD 23439B 5138.0Å to 5140.5Å. In each panel the solid line is computed for the derived isotopic ratios for that star, and the dashed line for the derived ratios for the other star. The derived ratios (Table 1) are ^{24}Mg:^{25}Mg:^{26}Mg = 78:13:9 for HD 23439A and ^{24}Mg:^{25}Mg:^{26}Mg = 84:8:8. for HD 23439B.

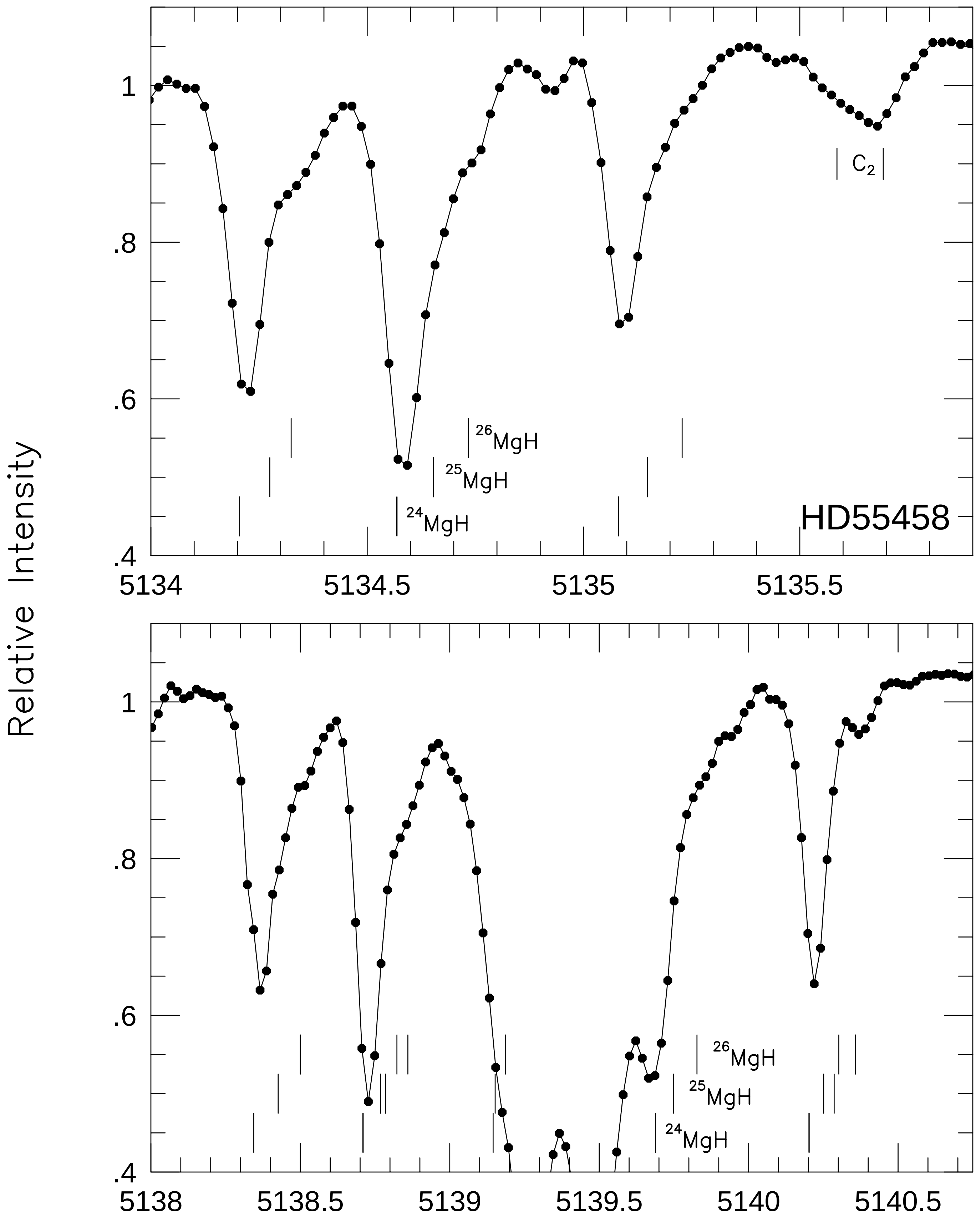


Relative Intensity
1
.8
.6
.4
.2
0
5132
5134
5136
5138
5140
Wavelength (Å)
*
*
*

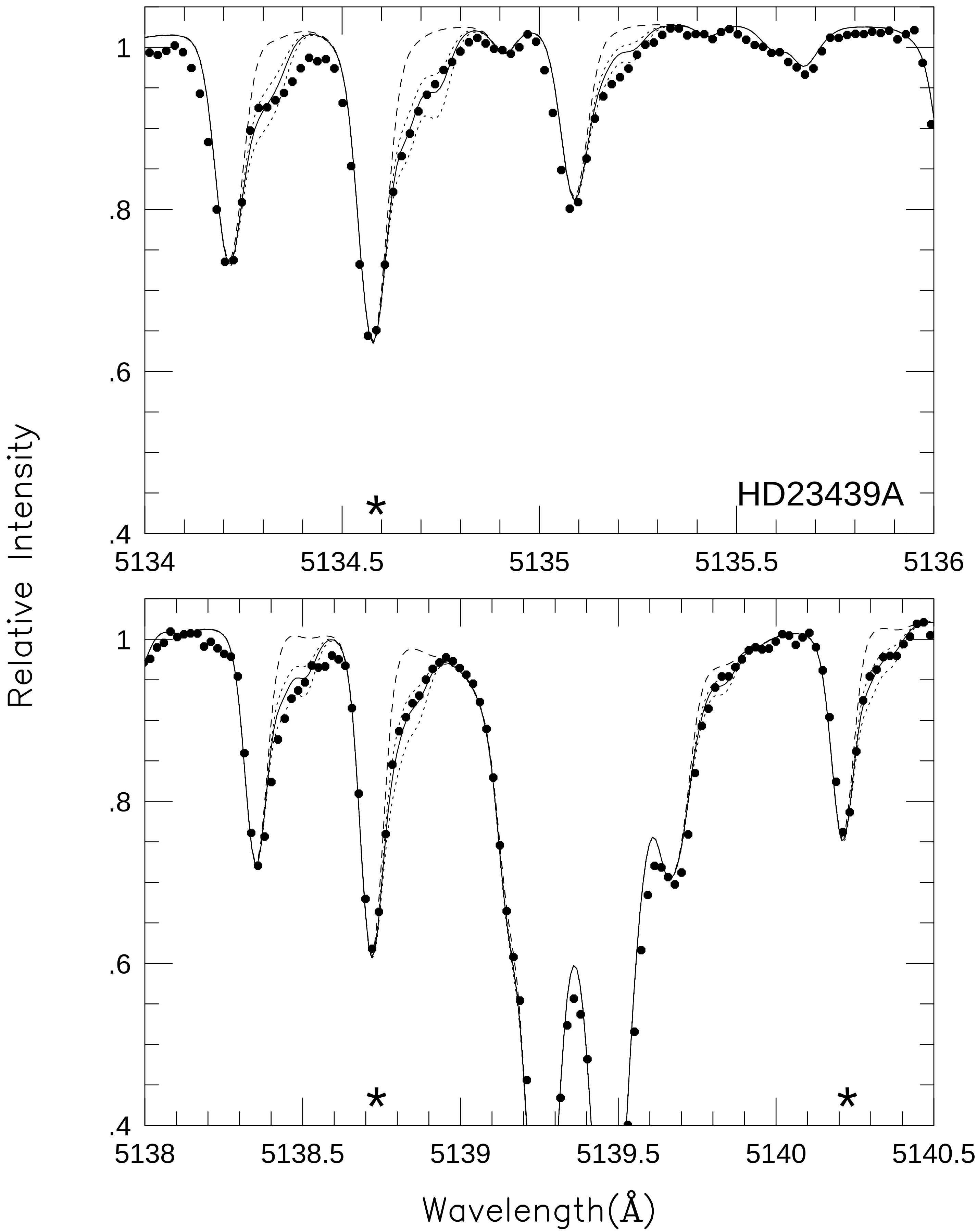
TABLE 1. The Program Stars

Star		T_{eff} (K)	log g (cgs)	[Fe/H] phot	[Fe/H] spec	[Fe/H] ref[a]	^{24}Mg:^{25}Mg:^{26}Mg
HD 6582	μ Cas	5350	4.6	–0.77	–0.85	TL99,F98	85:7:8
HD 10700	τ Cet	5330	4.4	–0.43	–0.59	TL99	75:15:9
HD 23439A		5060	4.6	–1.02	–1.05	TL99	78:13:9
HD 23439B		4710	4.7	–1.05	–1.11	TL99	84:8:8
HD 25329		4775	4.7	–1.63	–1.80	TL99,BS94	85:8:8
HD 26575	HR 1299	4190	2.3	···	–0.01	LS84	72:18:10
HD 55458	G88–14	5090	4.5	–0.32	–0.49	C94	75:15:9
HD 64606		5250	4.5	–0.85	–0.94	TL99,C99	82:10: 8
HD 65883		5300	4.4	–0.59	–0.82	TL99	82:10:7
HD 103095	Gmb 1830	5040	4.6	–1.33	–1.40	TL99,C99	93:4:3
HD 233832	BD+51°1664	4970	4.4	–0.53	–0.78	TL99	83:9:8
HD 108564		4660	4.6	–0.52	–1.18	TL99	80:11:9
HD 114095	G14-32	4680	2.4	–0.59	–0.35	C99	79:13:8
HD132142		5190	4.4	–0.26	–0.45	B99	82:8:10
HD 134439		5040	4.6	–1.33	–1.48	TL99,K97	91:6:3
HD 134440		4840	4.7	–1.24	–1.47	TL99, K97	91:6:3
HD 149661	12 Oph	5160	4.3	–0.08	0.01	M94	74:12:13
HD 165341	70 Oph	5030	4.2	–0.29	–0.10	MKB92	77:10:13
BD+37°1665	G87-27	5090	3.3	-0.43	-0.42	GL	85:9:6
BD-1° 1792	G112-36	4970	2.7	-0.84	-0.90	B99	87:7:7

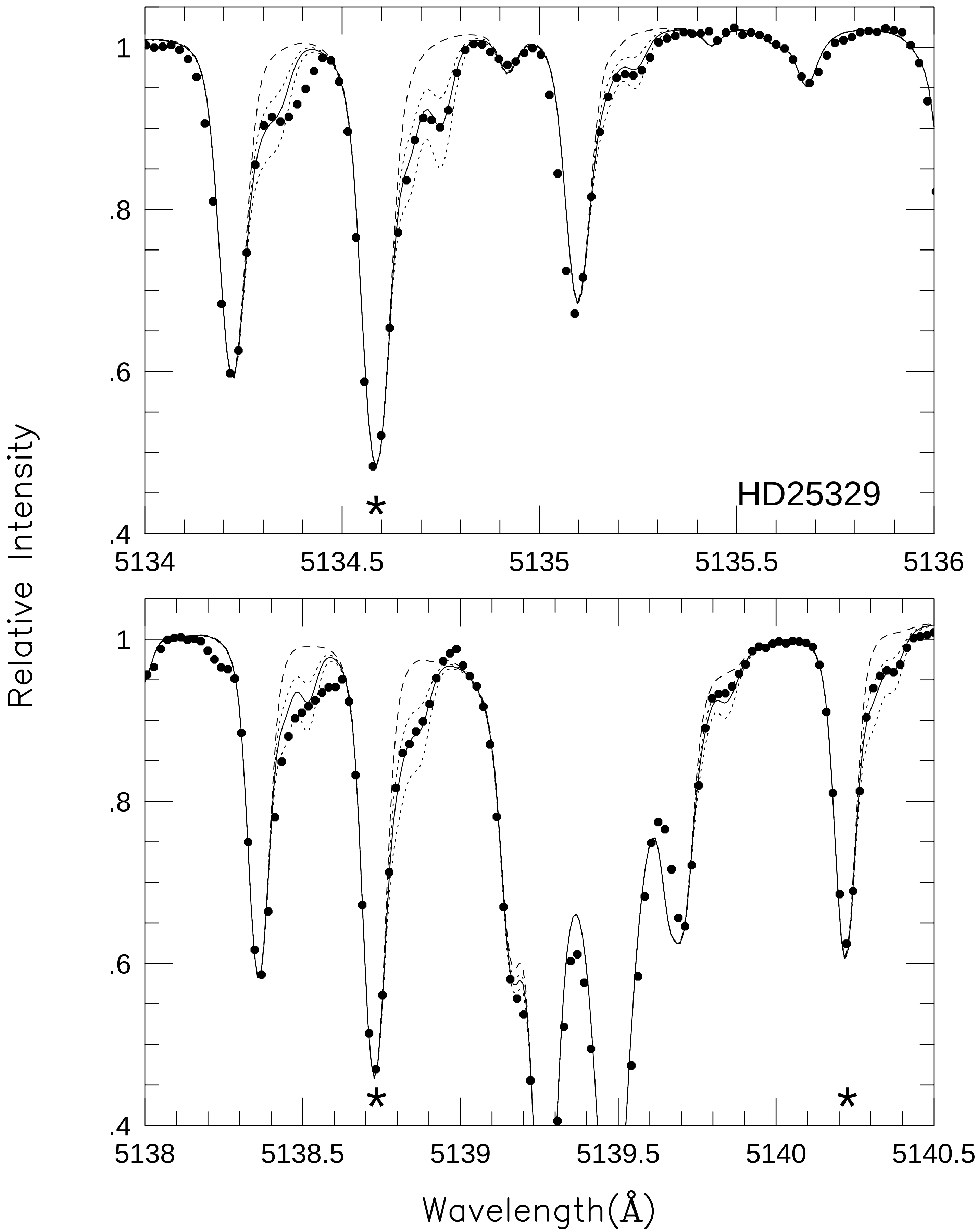
[a]References:
B99 = Beers et al. (1999)
BS94 = Beveridge & Sneden (1994)
C94 = Carney et al. (1994)
C99 = Clementini et al. (1999)
F98 = Fuhrmann (1998)
GL = This paper
K97 = King (1997)
LS84 = Lambert & Sawyer (1984)
MKB92 = Morell, Källender & Butcher (1992)
M94 = Morell (1994)
TL99 = Tomkin & Lambert (1999)

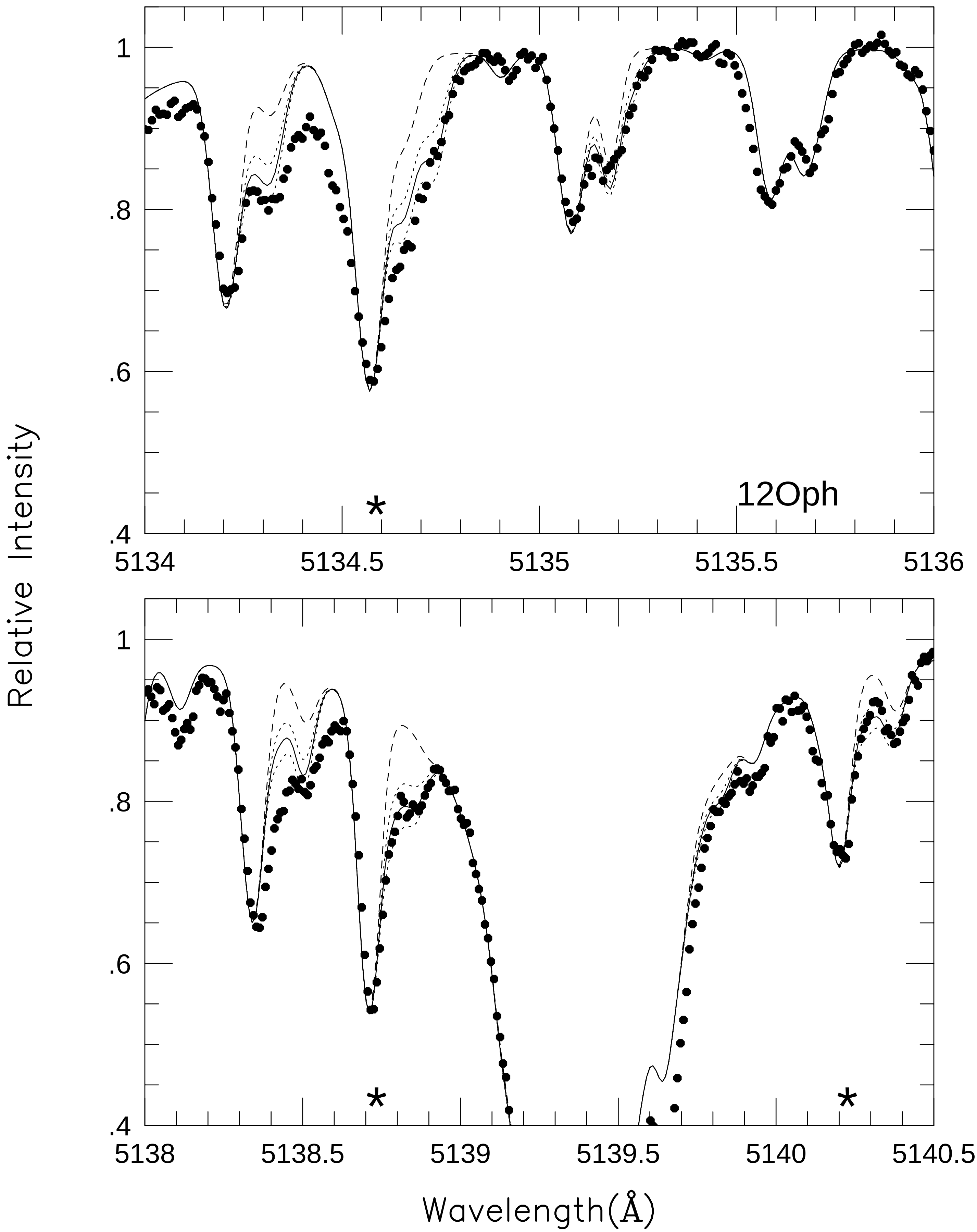


Relative Intensity
1
.8
.6
.4
C2
26MgH
25MgH
24MgH
HD55458
5134
5134.5
5135
5135.5
1
.8
.6
.4
26MgH
25MgH
24MgH
5138
5138.5
5139
5139.5
5140
5140.5
Wavelength (Å)

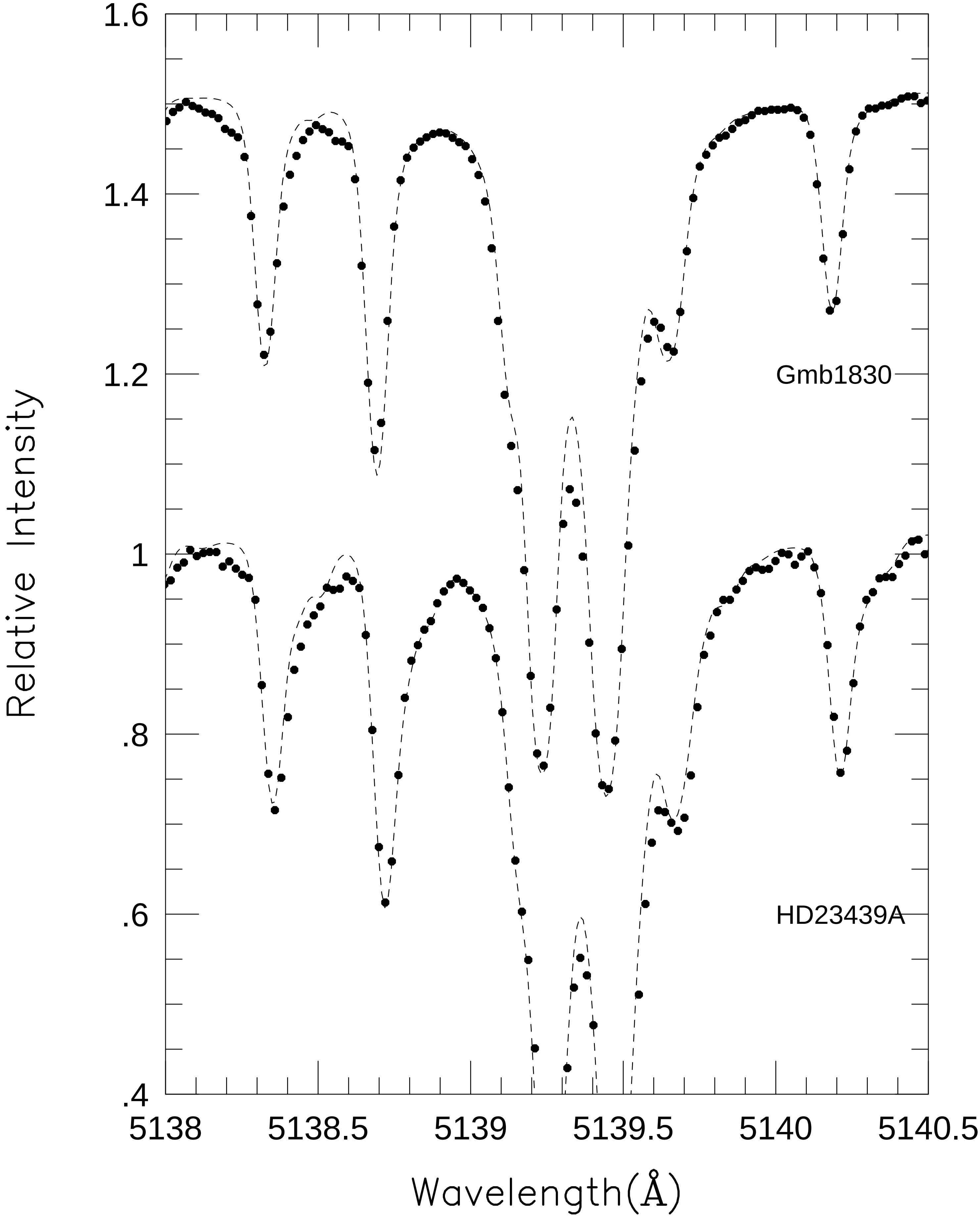


HD23439A
Relative Intensity
Wavelength(Å)

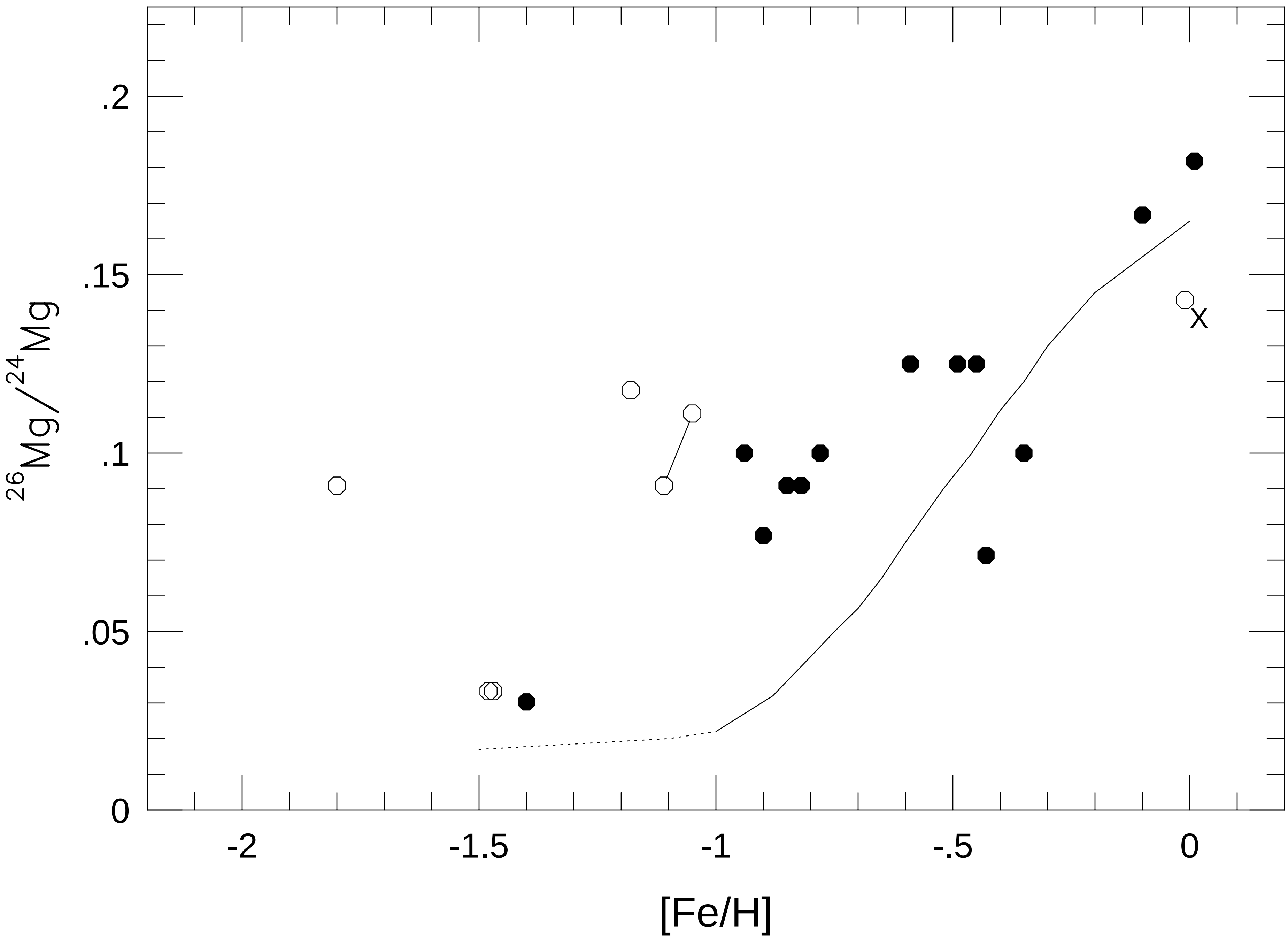

HD25329
Relative Intensity
Wavelength(Å)
5134
5134.5
5135
5135.5
5136
5138
5138.5
5139
5139.5
5140
5140.5
.4
.6
.8
1
*

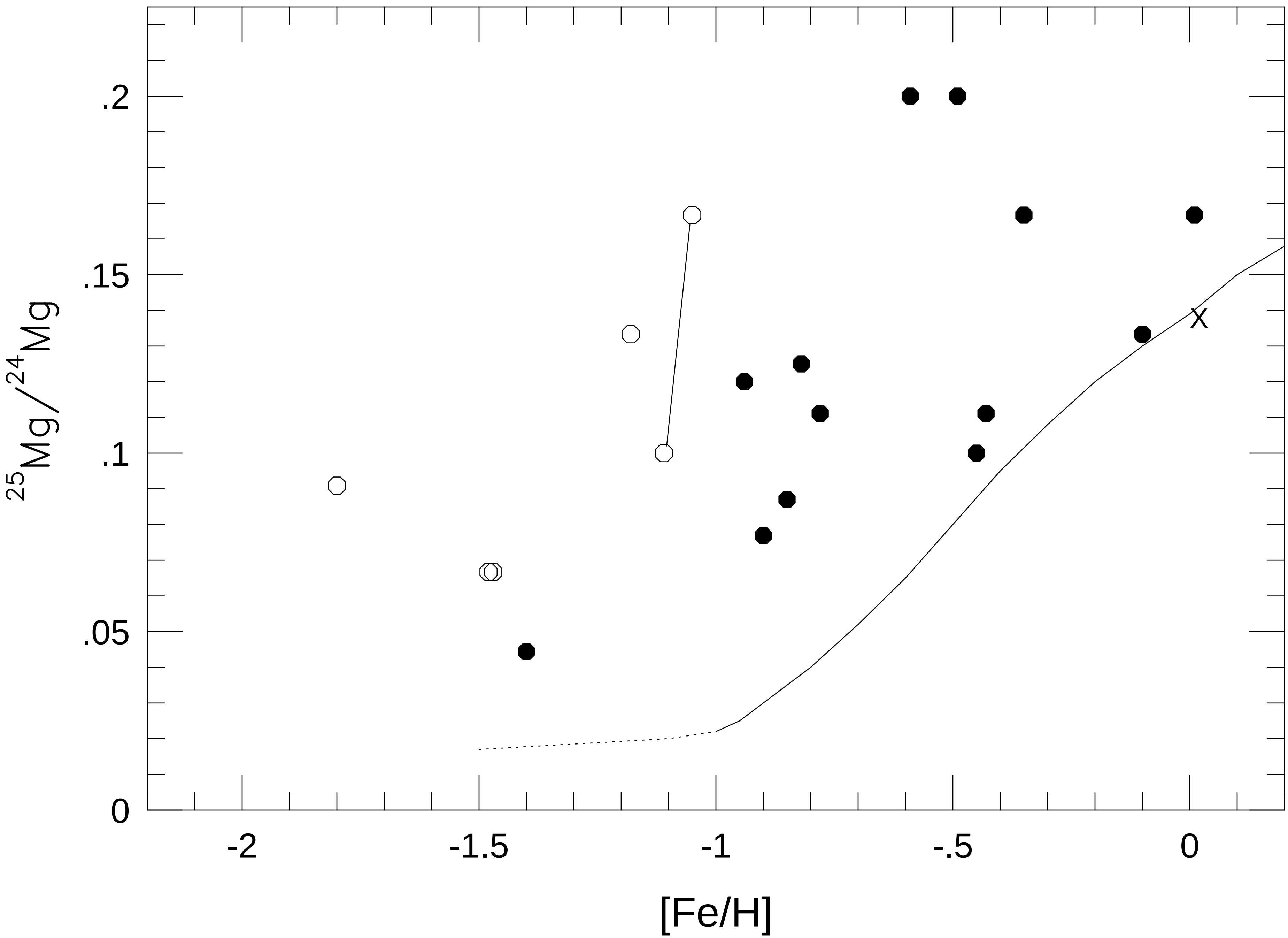


Relative Intensity
1
.8
.6
.4
12Oph
*
5134
5134.5
5135
5135.5
5136
*
*
5138
5138.5
5139
5139.5
5140
5140.5
Wavelength(Å)

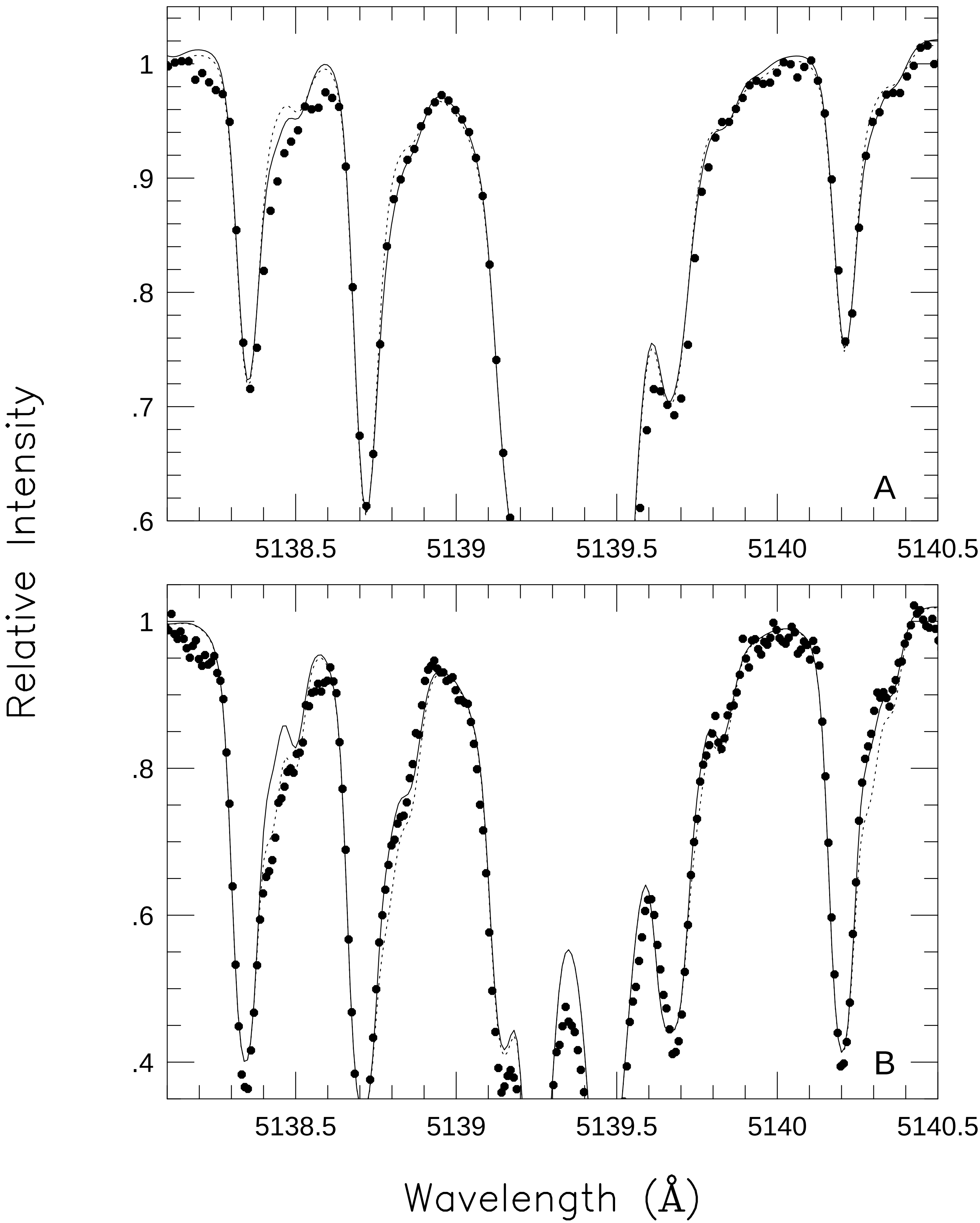


1.6
1.4
1.2
1
.8
.6
.4
Relative Intensity
Gmb1830
HD23439A
5138
5138.5
5139
5139.5
5140
5140.5
Wavelength(Å)


.2
.15
.1
.05
0
-2
-1.5
-1
-.5
0
[Fe/H]
$^{26}Mg/^{24}Mg$
X



.2
.15
.1
.05
0
-2
-1.5
-1
-.5
0
$^{25}Mg/^{24}Mg$
[Fe/H]
X



Relative Intensity
1
.9
.8
.7
.6
.4
A
B
5138.5
5139
5139.5
5140
5140.5
Wavelength (Å)